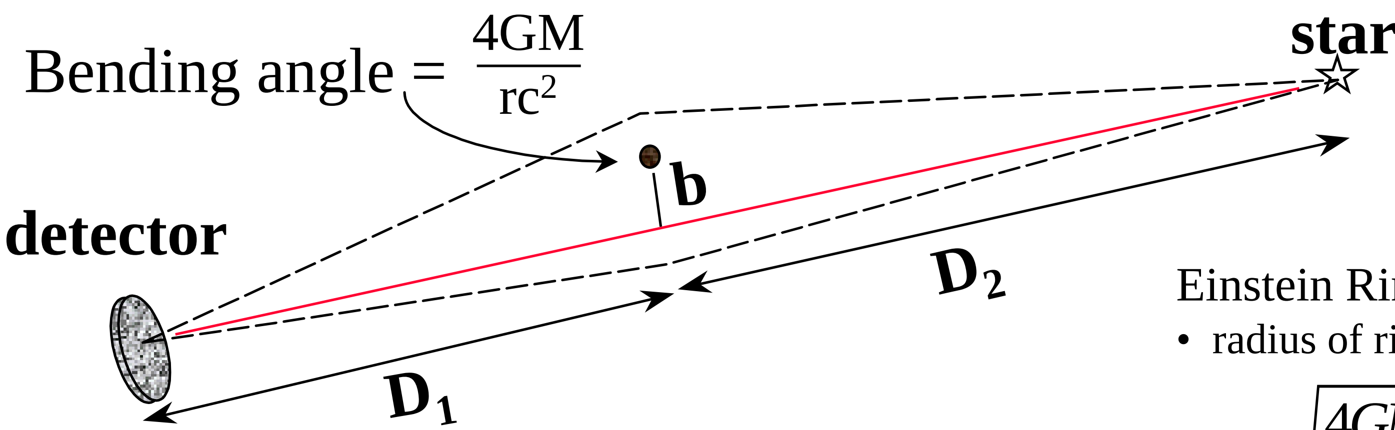
The Gravitational Microlensing Planet Search Technique from Space

David Bennett & Sun Hong Rhie (University of Notre Dame)

Abstract: Gravitational microlensing is the only known extra-solar planet search technique for which the amplitude of the planetary signals are independent of the planetary mass (for $M_{planet} > M_{Mars}$). Lower mass planets induce signals that are briefer and rarer than those of more massive planets, but if a very large number of main sequence stars are surveyed, it is possible to detect low-mass planets at high signal-to-noise. We explain the physics behind the gravitational microlensing planet search technique and explain why the planetary signals are large as long as the planet is massive enough to affect the light from most of the stellar disk at one time. A microlensing survey of main sequence source stars in the Galactic bulge will be sensitive to planets down to the mass of Mars, and we argue that such a survey must be done from space if definitive detections of Earth-mass planets are desired. We also compare to other indirect terrestrial planet search techniques and argue that a space-based gravitational microlensing program is the ***best*** method for detecting Earth-mass planets prior to the Terrestrial Planet Finder (TPF) mission. Such a mission is now under consideration for NASA’s Discovery Program, and further details about this Galactic Exoplanet Survey Telescope (**GEST**) mission can be found in posters **32.06** and **21.01**.

Poster 32.10 from the DPS 2000 meeting in Pasadena, CA, Oct. 23-27, 2000

The Principle of Gravitational lensing (single lens case)



Einstein Ring Radius: R_E

- radius of ring image for b = 0

$$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_1 D_2}{(D_1 + D_2)}}$$

For Galactic Microlensing, the image separation is < 1 mas, so images are not resolved. The observable parameter is the time varying magnification: A

$$A(u = 1) = 1.34$$

$$\Delta t \approx 3 \text{ days} \sqrt{\frac{M}{M_{jupiter}}}$$

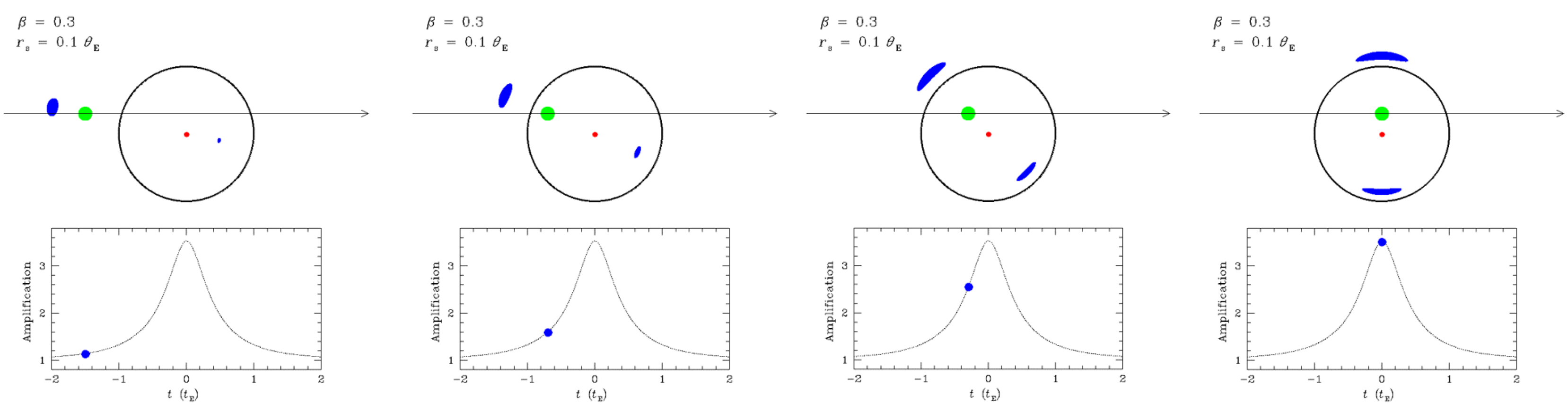
assumes $\sqrt{D}/v_\perp \approx \sqrt{2 \text{ kpc}}/(100 \text{ km/sec})$

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \quad \text{where} \quad u = \frac{b}{R_E}$$

so,

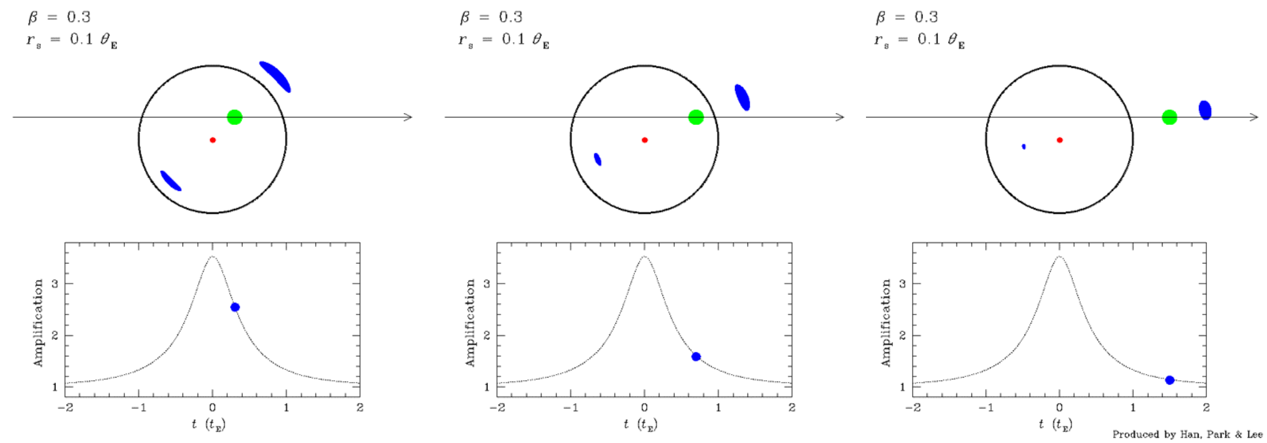
$$A \simeq \frac{1}{u} \text{ for } b \ll R_E$$

Gravitational Lensing Time Series for a Single Mass Lens System



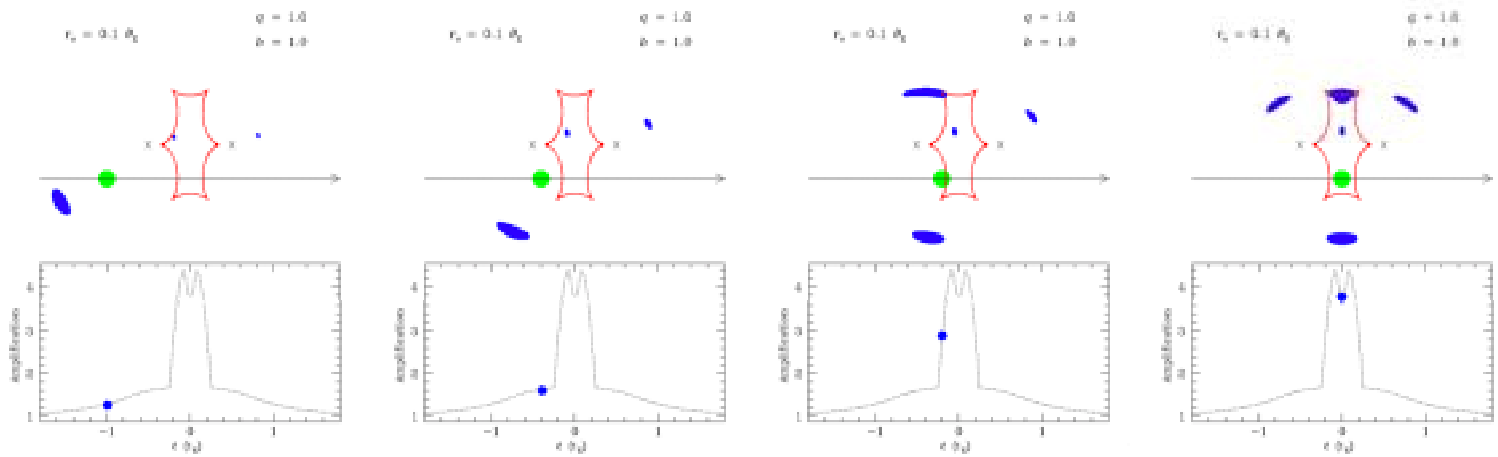
Maximum A = 3.3

● = source star size if unlensed,
● = lensed images,
● = lens location,
○ = Einstein ring



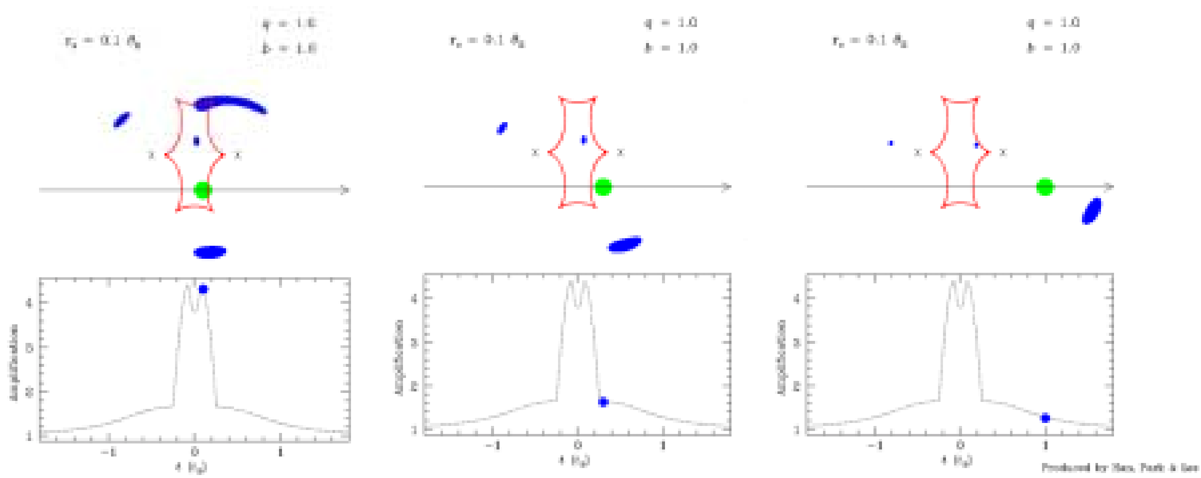
The image separation is < 1 mas, so only the total amplification, A, is observable. This is indicated by the ratio of the total area of the blue, lensed images compared to the green, unlensed image. A is shown at the bottom of each time series figure.

Gravitational Lensing Time Series for an Equal Mass Binary Lens System



Multiple lens systems are characterized by "caustic curves" as indicated in red above. When the source star crosses to the inside of a caustic curve, two new, high magnification, images are created.

When the source is inside the caustic, there are 5 images.



= source star size if unlensed,

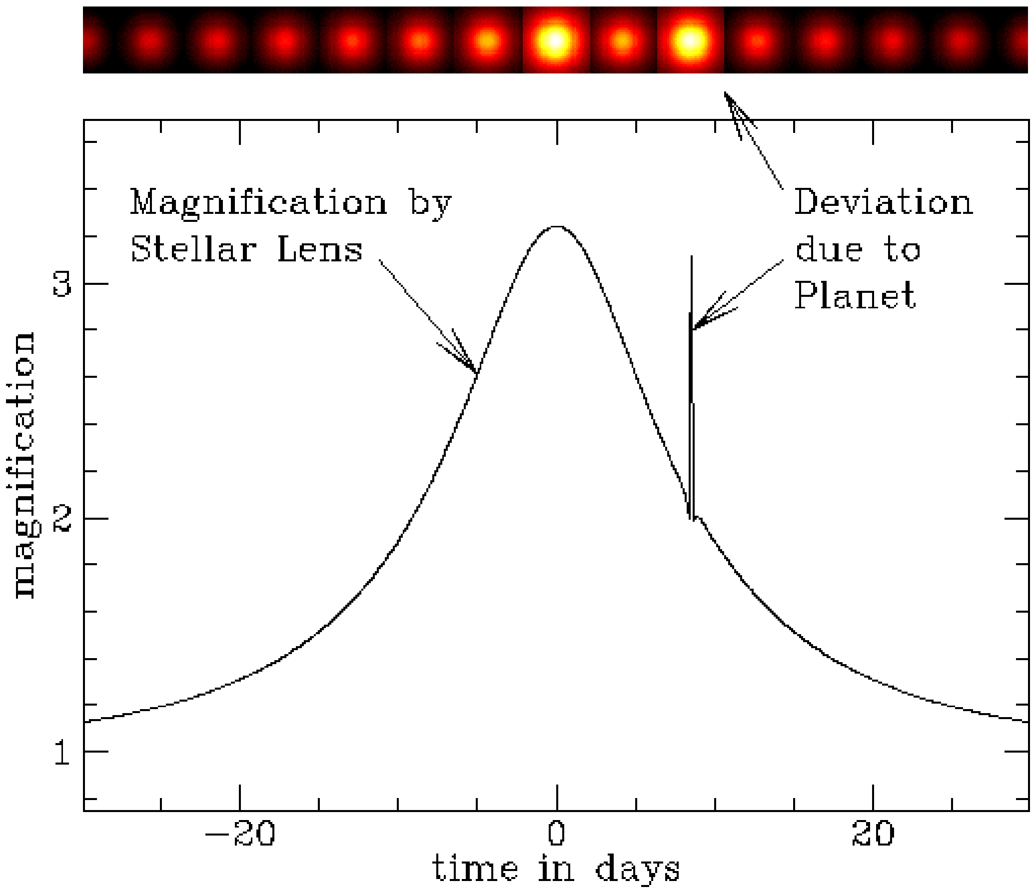
= lensed images,

× = lens location,

= caustic curve

As the sources starts to pass outside the caustic curve, two of the images brighten, and then merge and disappear creating a increase in brightness followed by a rapid decrease.

Planetary Microlensing Events Resemble Single Lens Events with a Brief Binary Lensing Episode



A planetary microlensing event light curve resembles a single lens light curve most of the time. But, if one of the lensed images approaches the location of a planet, then the light curve can have the strong caustic crossing features of a binary lens event.

How Likely is Stellar Microlensing?

Area on the sky covered by Einstein disks: $A = \underbrace{\pi R_E^2}_{\sigma} \underbrace{\left(\frac{M_{Gal}}{M_{Lens}}\right)}_{\text{\# of lenses}}$

Fractional area covered:

$$\tau \approx \frac{\pi \left(\frac{4GM_{Lens}}{c^2}\right)\left(\frac{R_{Gal}}{2}\right)\left(\frac{M_{Gal}}{M_{Lens}}\right)}{4\pi R_{Gal}^2}$$

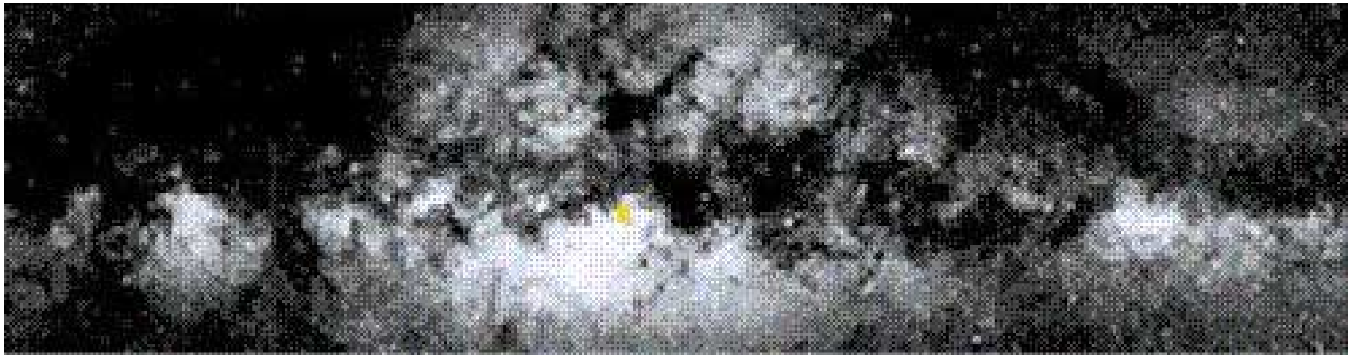
(assume that lenes dominate the total mass of the Galaxy)

$$\tau \approx \frac{GM_{Gal}}{R_{Gal}\,c^2}$$, but recall that $v_c^2 \approx \frac{GM_{Gal}}{R_{Gal}}$, so

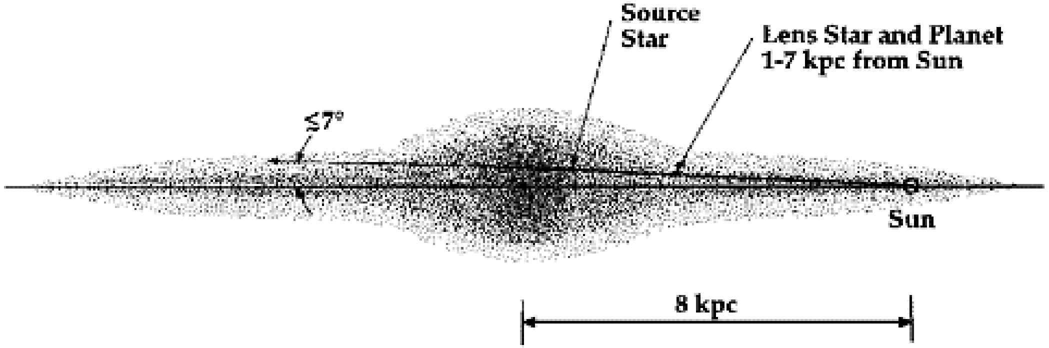
$$\boxed{\tau \approx \frac{v_c^2}{c^2} \approx \left(10^{-3}\right)^2 \approx 10^{-6}}$$

We need to monitor ~ 10^6 stars to see stellar microlensing and ~10^8 to detect terrestrial planets!

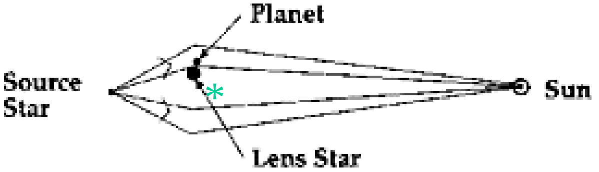
The Galactic Bulge is the Microlensing Planet Search Target Field



Optical view of the Galactic bulge. The central Galactic bulge has the largest microlensing probability and the highest density of source stars of any Galactic star field.



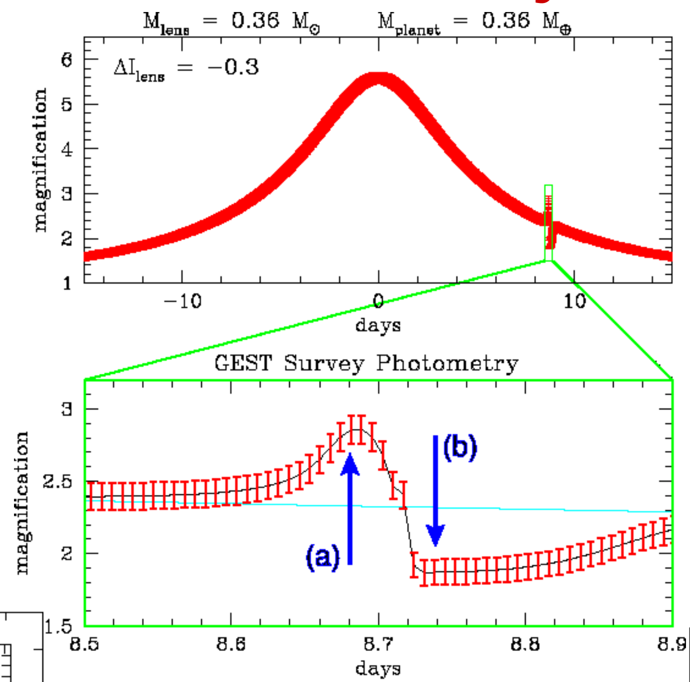
Side View



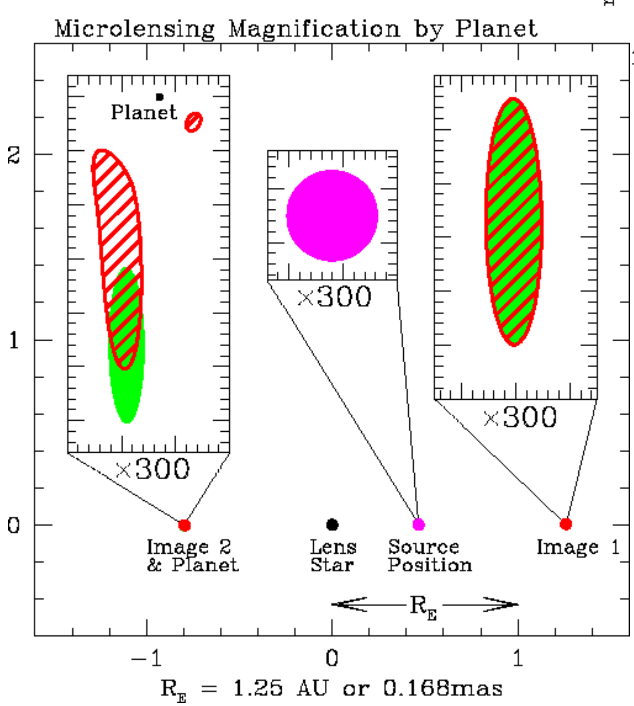
*binary lenses give 3 or 5 images - not 4

A Realistic Terrestrial Planetary Lensing Example

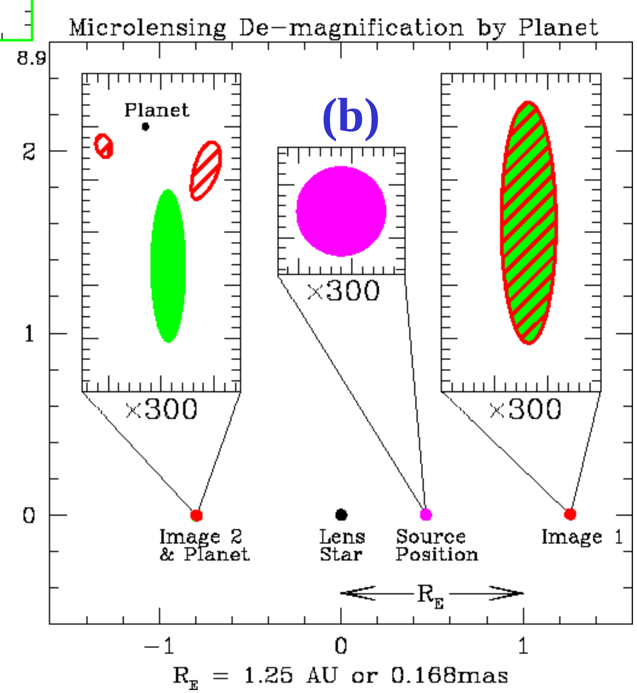
At right is an example light curve from the **GEST** mission (poster **32.06**). The error bars show the estimated 1σ measurement uncertainties for a simulated event, and the green box indicates the region of the planetary light curve deviation (expanded in the lower panel). The figures below show the lensed images at times **(a)** and **(b)** during the planetary deviation. The images are too small to see on the scale of the Einstein radius, R_E, so we have expanded them by a factor of 300 in order to display the relative sizes. The magenta spot shows the unlensed image size,



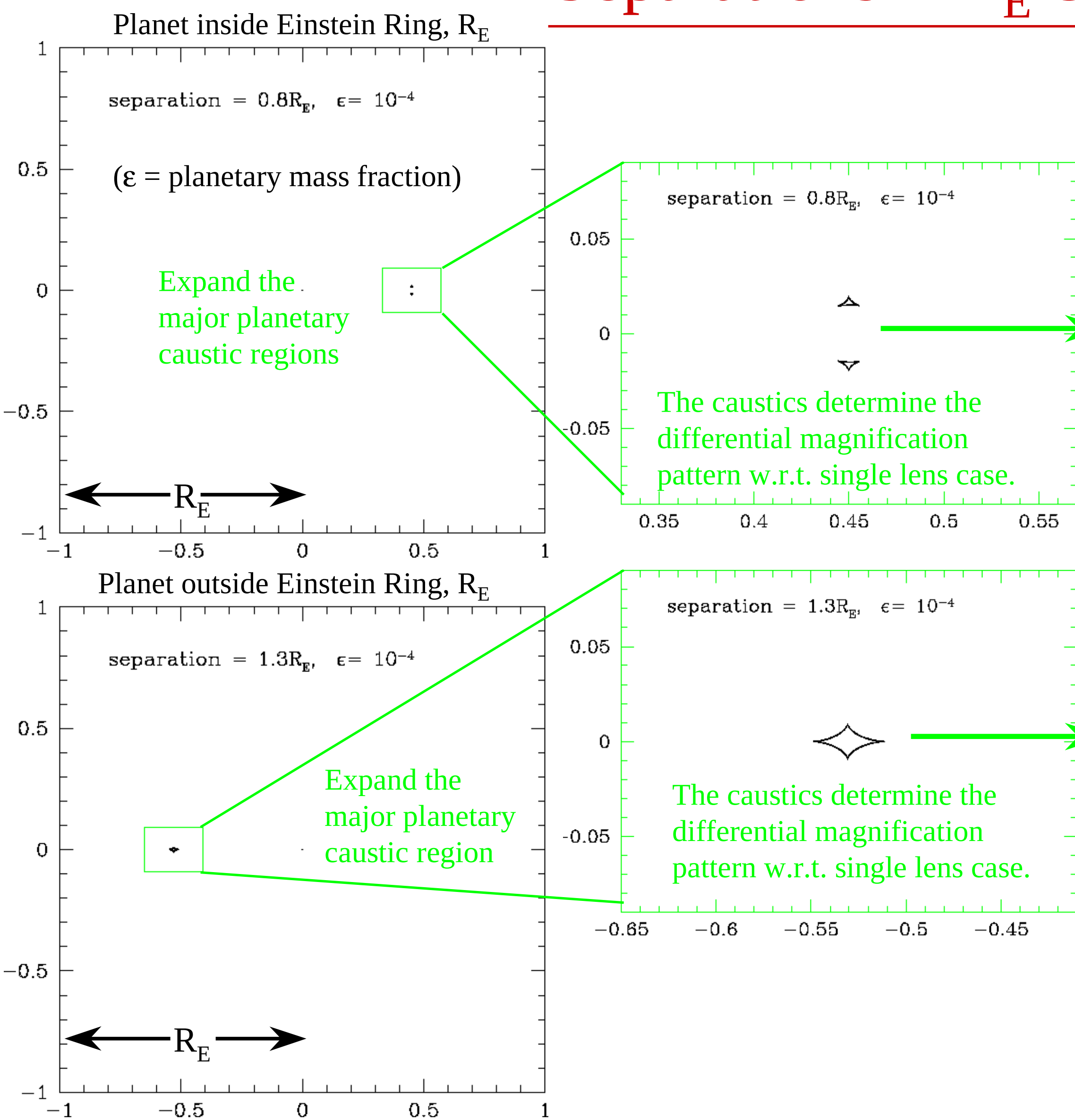
and the images lensed by the star are shown in green. These have about twice the area of the magenta image, so the total magnification due to the star is ~2. The red, cross-hatched images show the effect of a terrestrial planet located near image 2 (as shown). The planet does not effect image 1, but image 2 is split into 2 images which increase the total area of the lensed images at time **(a)**, and then decrease the total area of the lensed images at time **(b)**. The net result is a ~15% increase in magnification at time **(a)**, and a ~15% decrease in magnification at time **(b)**.

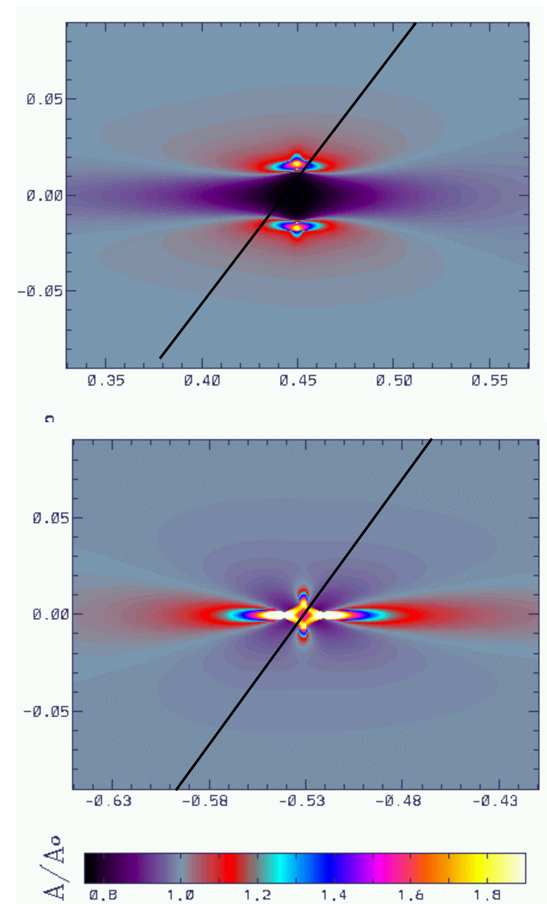


- unlensed image
- lensed by star
- lensed by star & planet



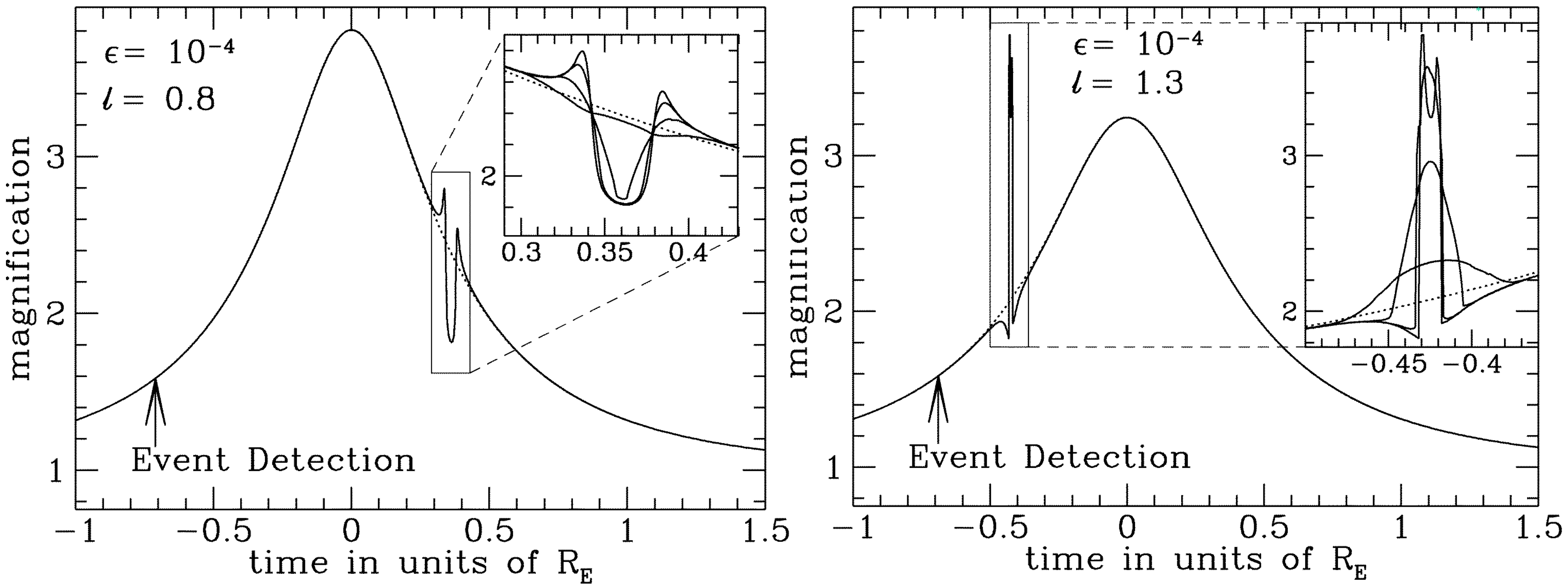
Planetary Light Curve Deviation Regions for Planets w/ Separations < R_E & > R_E





Differential magnification patterns with respect to the single lens case.

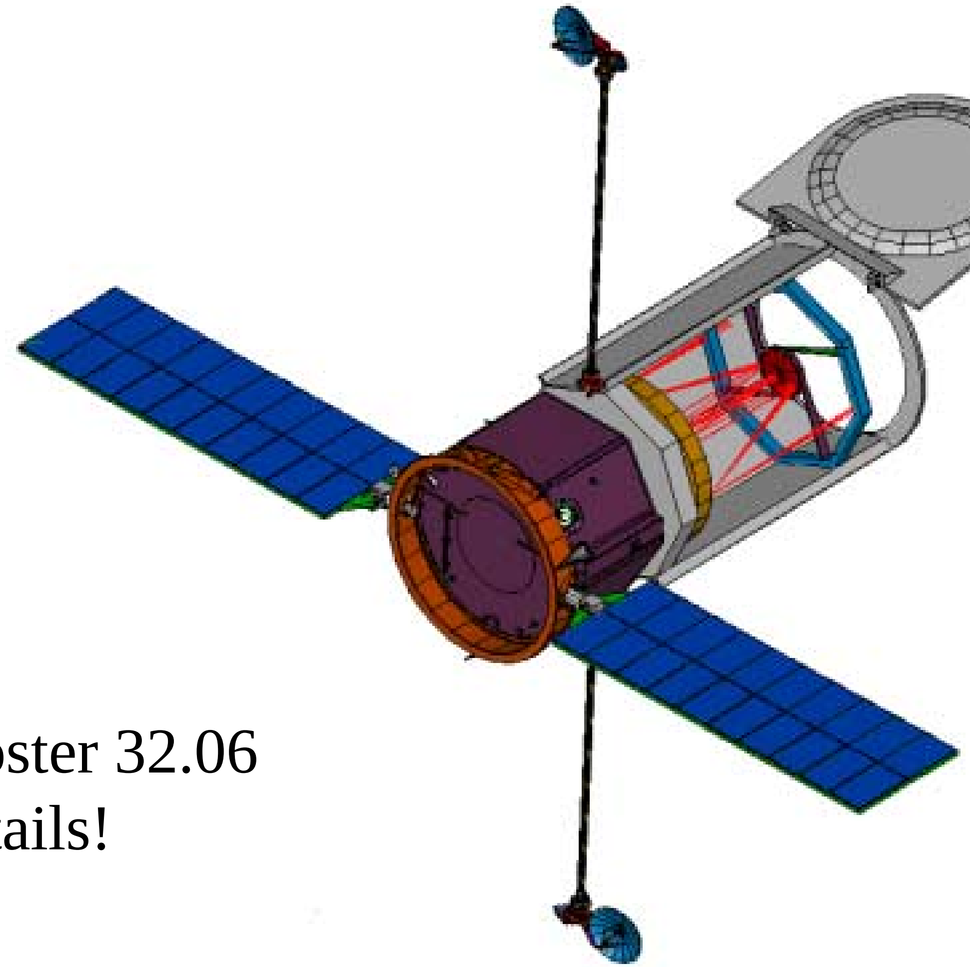
Planetary Light Curve Deviation Regions for Planets w/ Separations < R_E & > R_E (cont.)



Planetary lightcurves for planets at separations both inside and outside R_E. The source trajectories for these lightcurves are given by the dark diagonal lines which cross the upper and lower differential magnification panels in the figure on the right side of the previous page. The different light curves in the expanded planetary deviation region have different source star sizes, and the figure shows that the planetary deviations can get washed out for sufficiently large source sizes. For Galactic bulge main sequence source stars, the finite source effects only become important for planetary lens masses of < M_{mars}.

Note that both the inner and outer planetary deviations involve both a magnification increase and a magnification decrease with respect to the single lens light curve. These detection of these features make the microlensing light curves easy to classify and to distinguish from any non-planetary microlensing signals which might appear to resemble planetary microlensing events.

The Microlensing Technique is the Basis for the **G**alactic **E**xoplanet **S**urvey **T**elescope (**GEST**)

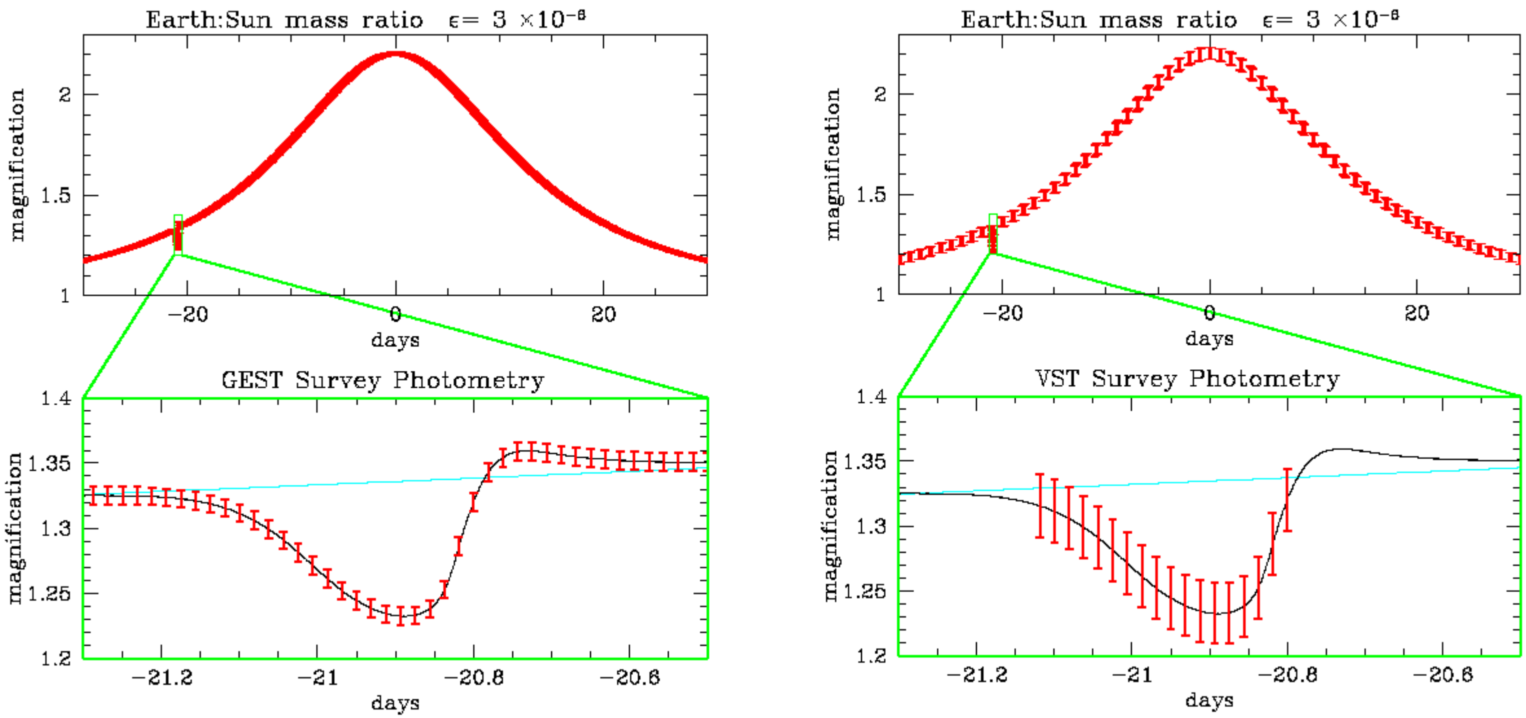


See poster 32.06
for details!

Why not find Earths via Microlensing from the Ground?

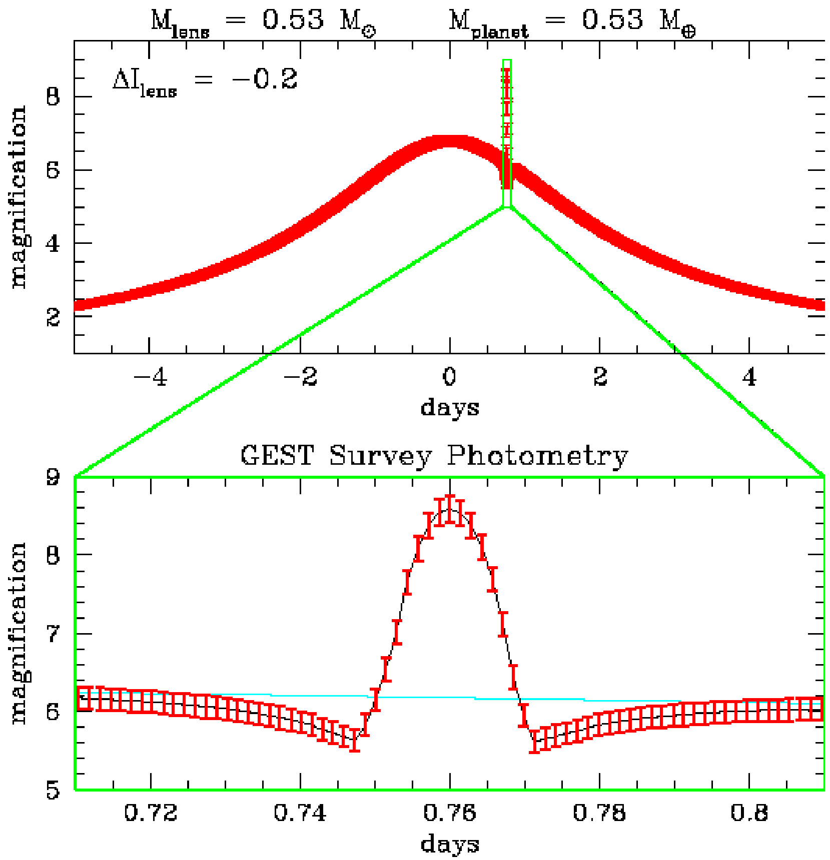
- Time coverage: we need continuous monitoring
  - poor light curve coverage => no definitive Earths
  - Observations from Chile, Australia, and South Africa can give ~24 hr. coverage
    - but, only Chile has excellent observing sites.
  - The South Pole can also give ~24 hr. coverage, but the seeing there is poor.
- Must observe main sequence source stars w/ ~1% photometric accuracy
  - >3 / square arc sec at our selected field
  - good seeing or very large telescope needed
  - requires >> 8m telescope in poor seeing sites like Australia or South Pole (median seeing ~2”)
  - Adaptive Optics systems do not have PSFs that are stable enough for good photometry

Why not find Earths via Microlensing from the Ground? (cont.)



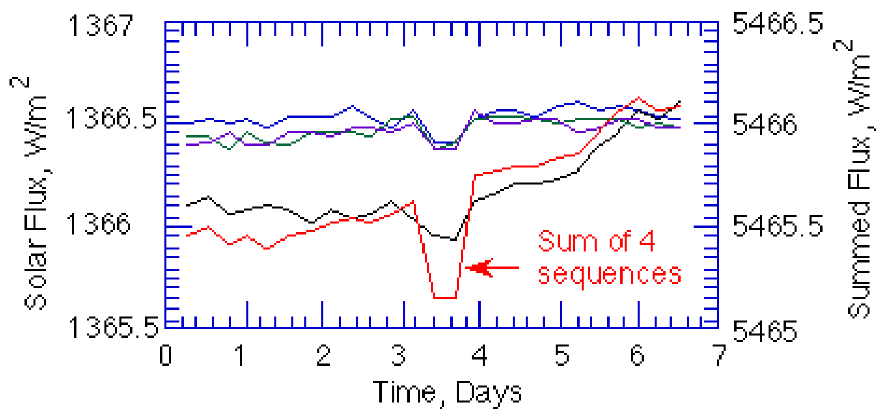
The Figures above show a comparison of a simulated terrestrial planet event as seen from a space-based telescope like GEST and a ground based survey using only a single site, Paranal in Chile, as suggested by Sackett (1997). Although larger telescope can be used from the ground, the ground-based seeing and sky background imply significantly poorer photometric accuracy even for relatively uncrowded stars such as the example shown above. Nevertheless, there are some events for which the signals of Earth-mass planets are large enough to be detected. Our simulations of a survey from a 2.5m wide-field imaging telescope (such as the VST) using ***100%*** of the observing time in the Galactic bulge season found that Earth-mass planets can be detected at about 2% of the rate from a space-based mission like GEST: *i.e.* 2 Earth-mass planets could be detected in 3 years with the requirement that most of their planetary light curve deviations must be visible from Paranal. However, the planetary signals see from Paranal would look like the light curve above on the right. While the planetary deviation is observed from Paranal, the lack of light curve coverage before and after the observations will prevent a determination of light curve parameters because we can't be sure that we've seen the entire signal. While larger telescopes such as VISTA or the LSST might offer some improvement, the available telescope time would be <<100% of the Galactic bulge season, and the light curve coverage would be too poor to determine accurate planetary parameters.

Comparison of Typical Microlensing & Transit Signals



A typical high S/N **GEST** “Earth” detection

- 45% planetary magnification signal with 2.5% errors
- 10% planetary de-magnification signals seen with many 3-4σ measurements
- overall S/N = 60 σ
- cannot be mimicked by non-planetary signals
- 1st discoveries within a few months



A typical “high S/N” Kepler “Earth” detection

- Kepler is a proposed space-based planetary transit detection mission
  - figure is from Kepler web page
- 12 hour transit duration = twice detection threshold of 6 hours
- Transit-like signals from random errors are about as frequent as transits, but periodic transits are significant.
- Sun-like photometry noise has a comparable amplitude to transits
  - as seen in the 4th transit signal
  - photometric noise timescale for the Sun is longer than for transits
  - Transit method can fail if most stars have more photometry noise than the Sun.
- overall S/N = 8.5 σ
- an eclipsing binary white dwarf yields a similar signal, so follow-up radial velocity observations are needed
- 1st discoveries take ~5 years (4 transits + follow-up observations)

Crucial Features of the Microlensing Technique

- The planetary signal strength is independent of mass
  - if $M_{planet} \geq M_{Mars}$
  - low-mass planet signals are brief and rare
- ~10% photometric variations
  - the required photometric accuracy has demonstrated w/ HST observations
  - >99% of stars are photometrically stable at the 1% level
- M_{planet}/M_{*} and separation are directly measured
- ~10^8 main sequence stars must be surveyed towards the Galactic bulge
- Planets are detected rapidly - even in ~20 year orbits
- the only method sensitive to old, free floating planets
  - short timescale single lens events
- can be done with current technology!
- **GEST** proposal is being considered for a Discovery Mission